Curious Variables Experiment (CURVE). IX Draconis - a Clue for Understanding Evolution of Cataclysmic Variable Stars

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Abstract

We report extensive photometry of frequently outbursting dwarf nova IX Draconis. During five months of observations the star went into three superoutbursts and seven ordinary outbursts. This allowed us to determine its supercycle and cycle lengths as equal to 54 ± 1 and 3.1 ± 0.1 days, respectively. During the September 2003 superoutburst, which had the best observational coverage, IX Dra displayed clear superhumps with a period of $P_{sh} = 0.066968(17)$ days (96.43 ± 0.02 min). This period was constant during the whole superoutburst. Another period, which was clearly present in the light curve of IX Dra in superoutburst, had a value of 0.06646(6) days (95.70 ± 0.09 min) and we interpret it as the orbital period of the binary. Thus IX Dra is the first SU UMa star showing orbital modulation during the entire superoutburst. The beat between these two periods is the main cause of an unusual phase reversal of superhumps - a phenomenon which was previously observed in ER UMa. If our interpretation of the second periodicity is correct, IX Dra has an extremely low period excess ε equal to only $0.76\% \pm 0.03\%$. This implies very low mass ratio $q = 0.035 \pm 0.003$, which strongly suggests that the system contains a brown dwarf-like degenerate secondary of mass $\sim 0.03\ \mathcal{M}_\odot$ and that IX Dra is the most evolved dwarf nova known.

Such a very low mass ratio results in the outer edge of the accretion disk reaching 80% of the distance between the components of the system. In turn, this allows the disk particles to enter a 2:1 resonance and leads to the appearance of the orbital period in the light curve of the entire superoutburst.

The high level of activity and brightness of IX Dra indicate that very old cataclysmic variables go through episodes of increased activity leading to loss of angular momentum through mass loss from the system.

Modulations with the orbital period are also detectable during normal outbursts and in quiescence.

Key words: Stars: individual: IX Dra – binaries: close – novae, cataclysmic variables

1 Introduction

Dwarf novae are non-magnetic cataclysmic variables, which are close binary systems containing white dwarf primary and Roche lobe filling secondary. The secondary is typically a low mass main sequence star, which loses its material through the inner Lagrangian point. This material forms an accretion disc around a white dwarf (Warner 1995).

One of the most intriguing classes of dwarf novae are SU UMa stars which have short orbital periods (less than 2.5 hours) and show two types of outbursts: normal outbursts and superoutbursts. Superoutbursts are typically about one magnitude brighter than normal outbursts, occur about ten times less frequently and display characteristic tooth-shape light modulations with a period a few percent longer than the orbital period of the binary.

The behavior of SU UMa stars in now well understood within the frame of the thermal-tidal instability model (see Osaki 1996 for review). Superhumps occur at a period slightly longer than the orbital period of the binary system. They are most probably the result of accretion disc precession caused by gravitational perturbations from the secondary. These perturbations are most effective when disc particles moving in eccentric orbits enter the 3:1 resonance. Then the superhump period is simply the beat period between orbital and precession rate periods.

Over ten years ago, the diversity of behavior observed in cataclysmic variables seemed to be quite small. These variables were classified into few distinct groups which were clearly visible in the $P_{orb} - \dot{M}$ diagram (see for example Fig. 3 of Osaki 1996). There is a group of SU UMa stars located below the period gap. At longer orbital periods one can find three other groups: U Gem, Z Cam and nova-like stars, listed according to increasing $\dot{M}$.

At the beginning of the 1990s, the situation started to be more complicated. The systems showing superhumps were divided into four subgroups:

- ordinary SU UMa stars,
- permanent superhumpers - high accretion rate systems permanently in superoutbursts (Skillman and Patterson 1993),
- WZ Sge stars, characterized by an extremely long quiescent state, going into superoutburst every $\sim$10 years and showing no or infrequent ordinary outbursts,
- ER UMa stars - systems characterized by an extremely short supercycle (20-60 days), a short interval between normal outbursts (3-4 days) and small amplitude (3 mag) of superoutbursts (Kato and Kunjaya 1995, Robertson et al. 1995)

There are only five known ER UMa stars: ER UMa itself (Kato and Kunjaya 1995, Robertson et al. 1995), V1159 Ori (Robertson et al. 1995, Patterson et al. 1995), RZ LMi (Robertson et al. 1995, Nogami et al. 1995), DI UMa (Kato et al. 1996) and IX Dra (Ishioka et al. 2001). The most poorly observed object in this group is IX Dra, thus we decided to include it in the list of stars observed within the Curious Variables Experiment (Olech et al. 2003a,b). Here we report the results of a five month observational campaign performed in 2003.

2 IX Draconis

The variability of IX Dra was discovered by Noguchi et al. (1982). The light curve obtained by Klose (1995) allowed him to determine the amplitude of light variations as equal to 3.5 mag and its period as equal to 45.7 days. These properties indicated that the star could be a CV system and thus IX Dra was classified as U Gem-type variable in the CV catalog of Downes et al. (1997). This classification was confirmed by spectroscopic observations of Liu et al. (1999).

IX Dra was extensively observed in 2000-2001 by Ishioka et al. (2001). Their observations revealed that the star is a member of the ER UMa-type group of variables, having a supercycle length of 53 days; an interval of normal outbursts of 3-4 days; a duty cycle $\sim$ 30% and an outburst amplitude of 2.5 mag. From time-series observations during the superoutbursts, they obtained a presumable superhump period of 0.067 days.

3 Observations and Data Reduction

Observations of IX Dra reported in the present paper were obtained during 46 nights between June 24, 2003 and November 22, 2003 at the Ostrowik station of the Warsaw University Observatory. The data were collected using the 60-cm Cassegrain telescope equipped with a Tektronics TK512CB back-illuminated CCD camera. The scale of the camera was 0.76"/pixel providing a 6.5'$\times$6.5' field of view. The full description of the telescope and camera was given by Udalski and Pych (1992).

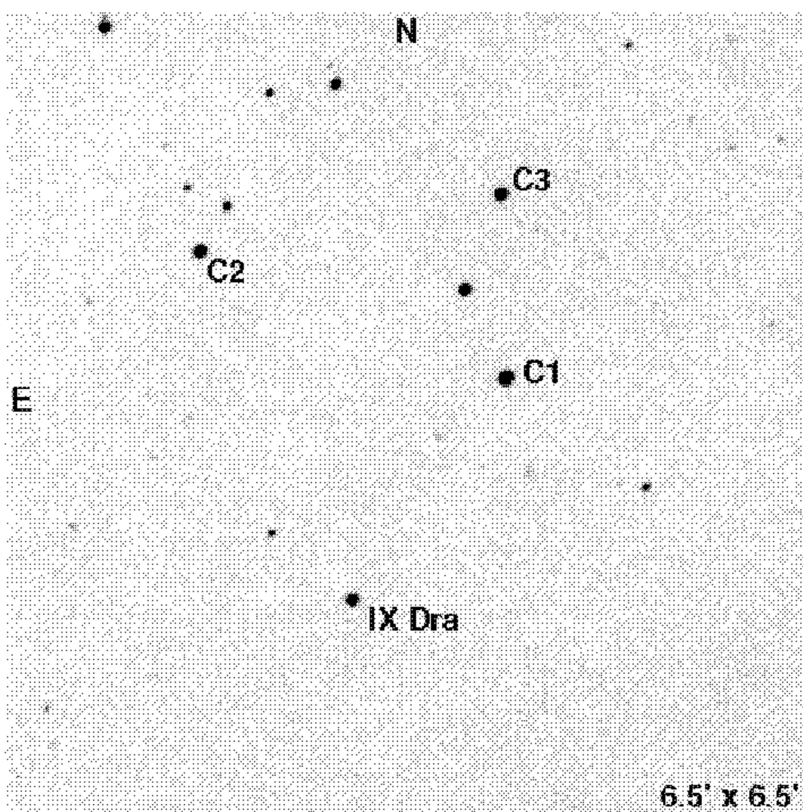

Figure 1: Finding chart for IX Dra covering a region of 6.5×6.5 arcminutes. The positions of the comparison stars are shown. North is up, East to the left.

We monitored the star in “white light” in order to be able to observe it also at minimum light of around 17.5 mag.

The exposure times were from 90 to 180 seconds during the bright state and from 150 to 350 seconds at minimum light.

A full journal of our CCD observations of IX Dra is given in Table 1. In total, we monitored the star for 141 hours and obtained 2759 exposures.

Table 1: JOURNAL OF THE CCD OBSERVATIONS OF IX DRA.

Date of 2003	Start 2452000. +	End 2452000. +	Length [hr]	No. of frames
Jun 24/25	815.35902	815.37233	0.319	5
Jun 25/26	816.42810	816.43371	0.135	4
Jun 26/27	817.44616	817.51757	1.714	43
Jun 28/29	819.39763	819.46972	1.730	37
Jun 30/01	821.41308	821.51691	2.492	32
Aug 04/05	856.46990	856.56842	2.364	60
Aug 05/06	857.50050	857.56902	1.644	46
Aug 06/07	858.31611	858.57326	3.677	101
Aug 08/09	860.32764	860.49241	3.954	60
Aug 16/17	868.37691	868.53273	3.740	96
Aug 17/18	869.36583	869.45143	2.054	47
Aug 20/21	872.39664	872.48818	2.197	41
Aug 22/23	874.37718	874.51764	3.371	61
Aug 23/24	875.53634	875.59433	1.392	34
Aug 24/25	876.55043	876.55399	0.085	3
Aug 25/26	877.40600	877.51050	2.508	38
Aug 27/28	879.46050	879.56141	2.421	47
Aug 28/29	880.31593	880.36075	1.076	23
Aug 30/31	882.31985	882.50416	4.423	124
Aug 31/01	883.33636	883.49807	3.881	62
Sep 01/02	884.47388	884.55306	1.900	10
Sep 02/03	885.51654	885.60859	2.209	47
Sep 03/04	886.32950	886.54790	5.242	111
Sep 05/06	888.40253	888.55522	3.665	93
Sep 06/07	889.30712	889.56523	6.195	141
Sep 07/08	890.31662	890.56445	5.948	133
Sep 13/14	896.30359	896.54744	5.852	126
Sep 14/15	897.29154	897.61492	2.811	76
Sep 15/16	898.56906	898.59302	0.575	17
Sep 16/17	899.50051	899.51023	0.233	5
Sep 20/21	903.43127	903.60900	4.265	76
Sep 21/22	904.24650	904.60668	8.644	161
Sep 22/23	905.23879	905.58645	8.344	151
Sep 24/25	907.24152	907.58795	8.314	127
Sep 25/26	908.24563	908.63513	9.348	172
Sep 26/27	909.24138	909.63448	9.434	154
Sep 30/01	913.35124	913.51222	0.681	13
Oct 01/02	914.43357	914.48948	1.342	24
Oct 03/04	916.24779	916.30463	1.364	20
Oct 15/16	928.32350	928.34468	0.508	12
Oct 18/19	931.26054	931.37863	1.146	24
Oct 19/20	932.32327	932.37064	1.137	14
Oct 31/01	944.40016	944.41475	0.350	6
Nov 19/20	963.63478	963.66356	0.691	9
Nov 20/21	964.34627	964.66717	2.042	15
Nov 22/23	966.20520	966.70929	3.643	58
Total	–	–	140.1	2759

All the data reductions were performed using a standard procedure based on the IRAF[1] package and profile photometry was derived using the DAOphotII package (Stetson 1987).

Relative unfiltered magnitudes of IX Dra were determined as the difference between the magnitude of the variable and the intensity averaged magnitude of three comparison stars shown on finding chart in Fig. 1. The magnitudes and colors of our comparison stars were taken from Henden and Honeycutt (1995) and are summarized in Table 2.

The typical accuracy of our measurements varied between 0.004 and 0.090 mag depending on the brightness of the object. The median value of the photometric errors was 0.015 mag.

[1]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

Table 2: PROPERTIES OF COMPARISON STARS USED FOR CALIBRATION OF IX DRA MAGNITUDE.

Star	R.A. 2000.0	Decl. 2000.0	V	$B-V$
C1	$18^h12^m19.6^s$	67°06′26.7”	14.524	1.116
C2	$18^h12^m43.4^s$	67°07′24.6”	14.652	0.704
C3	$18^h12^m19.9^s$	67°07′20.1”	14.727	0.463

The $B-V$ color of outbursting novae is ~ 0 mag (Bruch and Engel 1994). Frequently outbursting ER UMa stars have $B-V \approx 0$ even in quiescence due to large mass transfer rates. Thus the most appropriate star for transforming the relative light curve to the Johnson V system is the bluest star, $C3$. Our observations were made in "white light", which roughly corresponds to Cousins R band (Udalski and Pych 1992). Knowing the $B-V$ color of $C3$ we can estimate its $V-R$ color which is ~ 0.27 mag (Caldwell et al. 1993). Using this value and V magnitude of $C3$ we transformed our relative light curve to the Johnson V system.

4 General light curve

The nightly light curves were intensity averaged into one-day bins for runs shorter than four hours and in half-day bins for longer runs. The resulting light curve for the period August-November 2003 is shown in Fig. 2. In this interval, the star displayed three superoutbursts and six ordinary outbursts. A seventh outburst, not shown in Fig. 2, was additionally observed at the end of June 2003.

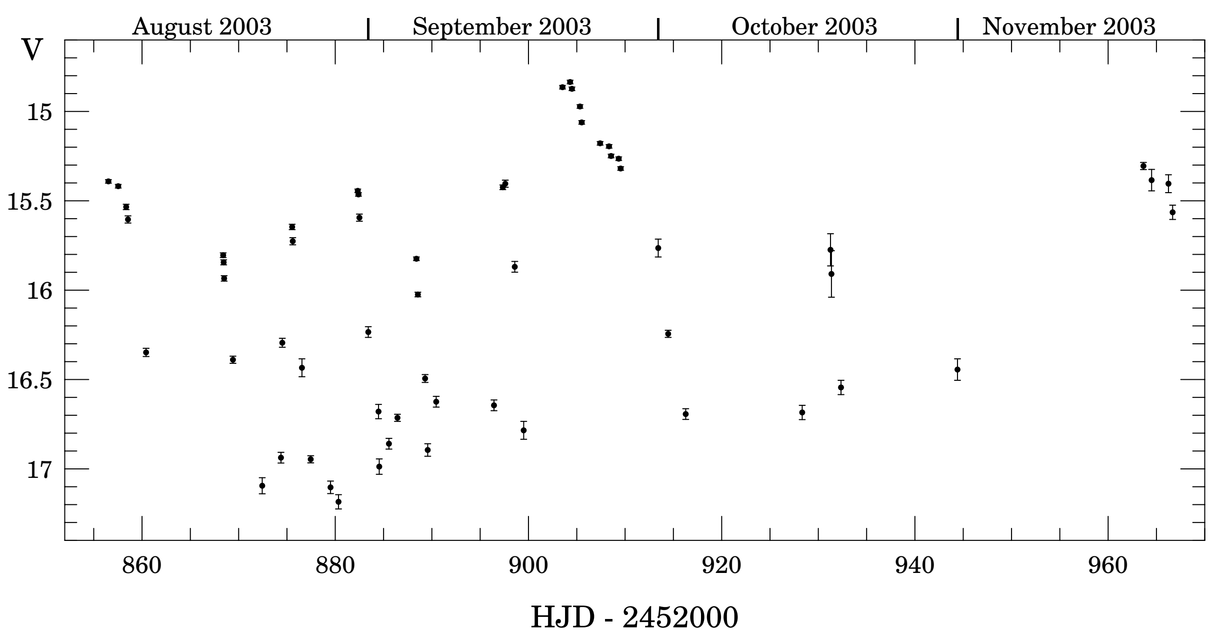

Figure 2: The general photometric behavior of IX Dra during our 2003 campaign.

The minimal brightness of the star in quiescence is 17.3 mag. In the superoutburst, IX Dra reaches 14.8 mag, and in ordinary outbursts around 15.4 mag.

The general light curve of IX Dra was analyzed using ANOVA statistics with two harmonic Fourier series (Schwarzenberg-Czerny 1996). The resulting periodogram, for the frequency range $0 \div 0.6$ c/d, is shown in Fig. 3. Two dominant peaks correspond to the periods 54 ± 1 and 3.1 ± 0.1 days, which can be interpreted as intervals between two consecutive superoutbursts and ordinary outbursts, respectively. These values are in very good agreement with results obtained by Ishioka et al. (2001). One can note the increasing length of the supercycle: in the first half of the 1990s it was 45.7 days (Kolb 1995), already 53 days (Ishioka et al. 2001) in the years 2000-2001 and 54 days in 2003. Changes of the supercycle length were observed in other ER UMa-type variables. ER UMa itself showed increase of supercycle with rate of $\dot{P} \approx 4 \times 10^{-3}$ and RZ LMi decrease with rate of $\dot{P} = -1.7 \times 10^{-3}$ (Robertson et al. 1995).

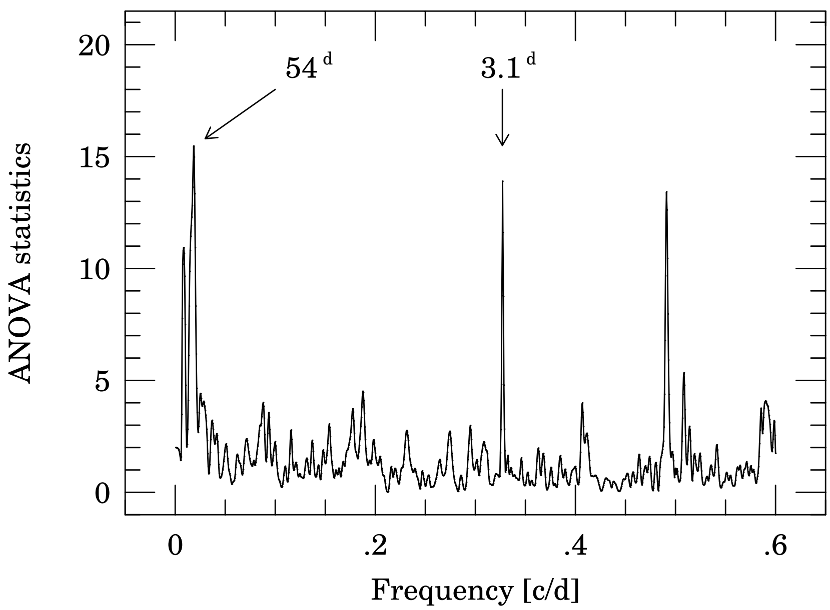

Figure 3: The power spectrum of IX Dra global light curve. The arrows mark the position of most prominent peaks corresponding to periods 54 and 3.1 days.

The general light curve of IX Dra in superoutbursts was folded on a supercycle period of 54 days and is displayed in Fig. 4. It is clear that the whole superoutburst lasts around 13 days and is divided into a quick initial rise ($<$ 1 day), a plateau phase ($\sim$ 10 days) and a final decline ($\sim$ 3 days). The decline rate is $0.078(2)$ mag $\cdot$ d^{-1} and $0.26(2)$ mag $\cdot$ d^{-1} during plateau and final decline phases, respectively.

The overall behavior of IX Dra is very consistent with the model of ER UMa-type variables computed by Osaki (1995). His bolometric light curve (see his Fig. 2), obtained for binary system with mass transfer rate of $\dot{M} = 4.0 \times 10^{16}$ g $\cdot$ s^{-1}, resembles our observations in all details. The model light curve shows superoutbursts occurring every 44 days, the duration of a superoutburst of 20 days and the recurrence time of normal outbursts of 4-5 days.

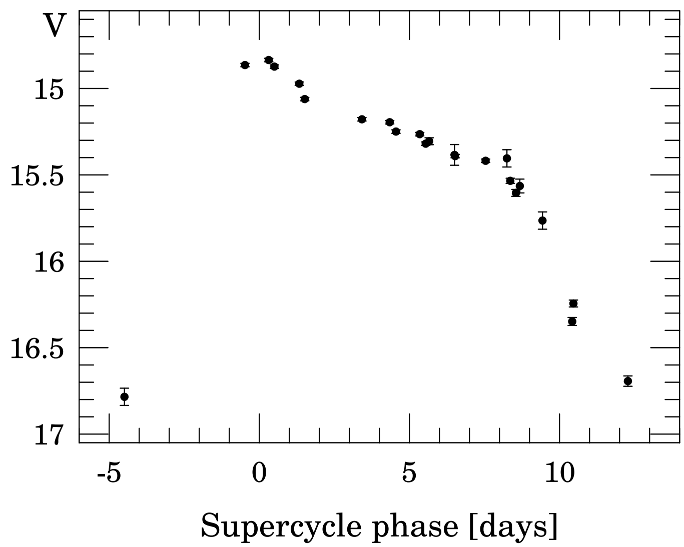

Figure 4: The light curve of IX Dra in superoutburst obtained by folding the general light curve with supercycle period of 54 days.

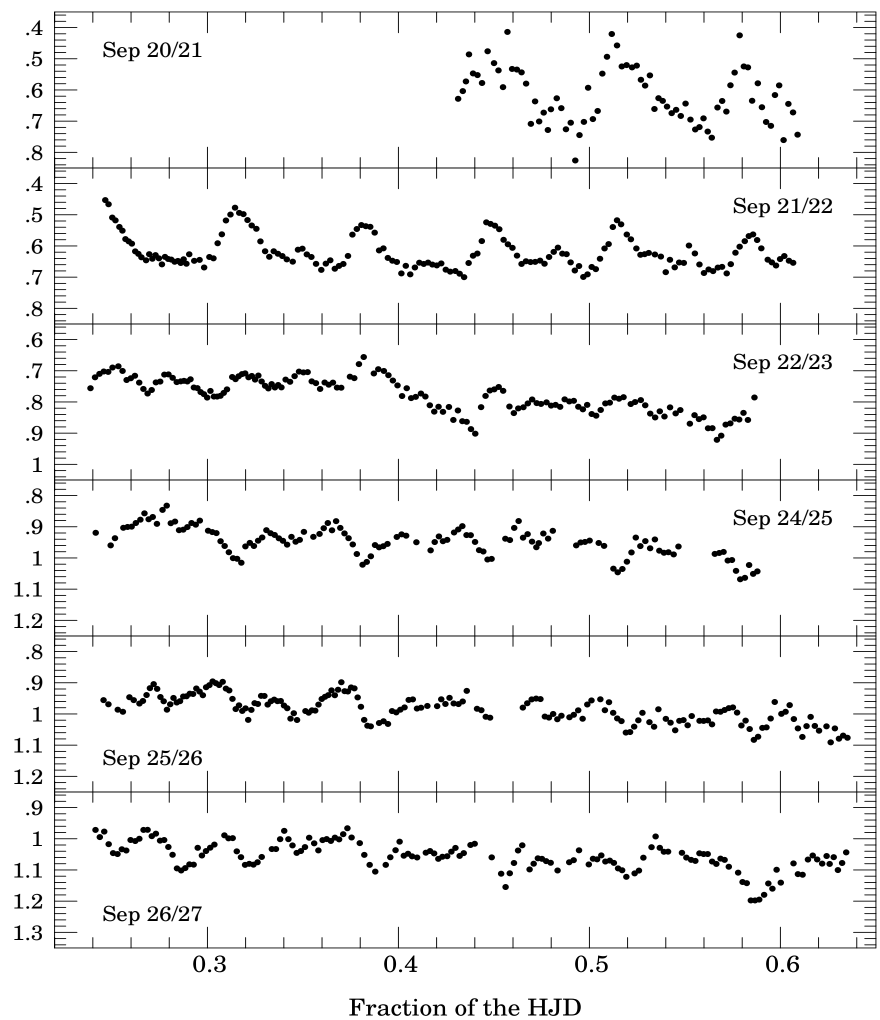

Figure 5: The light curves of IX Dra during its 2003 September superoutburst.

5 The September 2003 superoutburst

Our observations from Sep 20/21 caught IX Dra in a very bright state. Three nights earlier the star was in quiescence. The mean brightness of IX Dra at the beginning of the night of Sep 21/22 was even higher than on Sep 20/21, thus we conclude that the superoutburst started on Sep 20.

Light curve from nights Sep 20/21 and 21/22 shows well developed superhumps with an amplitude of 0.27 and 0.16 mag, respectively (see Fig. 5). On Sep 21, the clear secondary humps became visible. One night later, the amplitude of superhumps declined to 0.08 mag, and secondary humps were even more prominent, having an amplitude only slightly smaller than the main maxima. During the nights Sep 24/25, 25/26 and 26/27 the amplitudes of variability were 0.09, 0.08 and 0.08 mag, respectively. The shape of the superhump profile became complex and it was very difficult to say which maximum was the primary and which the secondary.

5.1 The $O-C$ analysis

To check the stability of the superhump period and to determine its value we constructed an $O-C$ diagram. We decided to use the timings of primary minima, because they were almost always deep and clearly visible in the light curve of the variable. In the end, we were able to determine 29 times of primary minima and they are listed in Table 3 together with their errors, cycle numbers E and $O-C$ values.

The least squares linear fit to the data from Table 3 gives the following ephemeris for the minima:

$$\mathrm{HJD}_{min} = 2452903.3966(12) + 0.066963(19) \cdot E \qquad (1)$$

The $O-C$ values computed according to the ephemeris (1) are listed in Table 3 and also shown in Fig. 6. It is clear that there is no trace of period change, thus we conclude that period of the superhumps during 2003 September superoutburst of IX Dra was constant and its value was $P_{sh} = 0.066963(19)$ days.

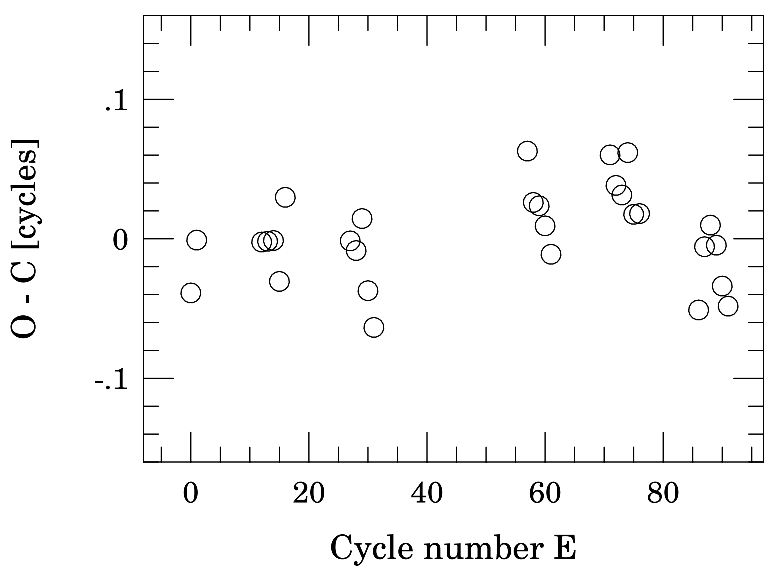

Figure 6: The $O-C$ diagram for superhumps minima of IX Dra detected during its 2003 September superoutburst.

Table 3: TIMES OF MINIMA IN THE LIGHT CURVE OF IX DRA DURING ITS 2003 SEPTEMBER SUPEROUTBURST.

Cycle number E	$HJD_{\rm min} - 2452000$	Error	$O-C$ [cyles]
0	903.4940	0.0045	−0.0388
1	903.5635	0.0030	−0.0009
12	904.3000	0.0030	−0.0023
13	904.3670	0.0040	−0.0018
14	904.4340	0.0025	−0.0012
15	904.4990	0.0030	−0.0305
16	904.5700	0.0040	0.0297
27	905.3045	0.0025	−0.0015
28	905.3710	0.0035	−0.0084
29	905.4395	0.0025	0.0145
30	905.5030	0.0040	−0.0372
31	905.5682	0.0040	−0.0635
57	907.3177	0.0030	0.0629
58	907.3822	0.0030	0.0261
59	907.4490	0.0040	0.0236
60	907.5150	0.0025	0.0093
61	907.5806	0.0030	−0.0111
71	908.2550	0.0060	0.0601
72	908.3205	0.0040	0.0383
73	908.3870	0.0030	0.0314
74	908.4560	0.0050	0.0618
75	908.5200	0.0030	0.0176
76	908.5870	0.0025	0.0181
86	909.2520	0.0025	−0.0510
87	909.3220	0.0025	−0.0057
88	909.3900	0.0030	0.0098
89	909.4560	0.0020	−0.0046
90	909.5210	0.0030	−0.0339
91	909.5870	0.0030	−0.0483

5.2 Nightly light curves

Knowing the period of superhumps we can phase the nightly light curves from superoutburst to trace the superhump profile changes. The result of such an operation is shown in Fig. 7. Phase 0.0 corresponds to a deep minimum in the light curve. It is clear that at the beginning of superoutburst, the star displayed large-amplitude tooth-shape superhumps with no secondary maxima. One night later, the amplitude significantly decreased, and secondary maxima became visible. On Sep 22, the amplitude of secondary humps increased, and on Sep 24 they became higher than the main maxima.

The situation repeated on nights Sep 25 and Sep 26.

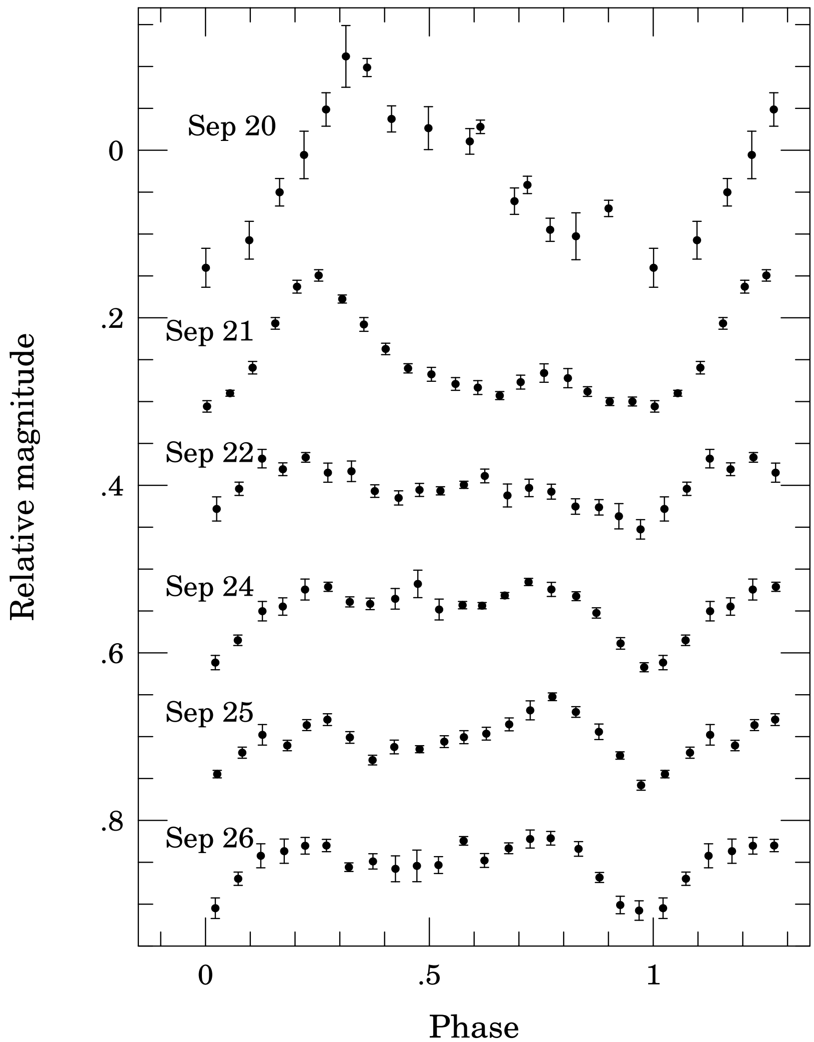

Figure 7: Amplitude and profile changes of superhumps during 2003 September superoutburst of IX Dra.

Such an unexpected phase reversal of maxima during the very early stage (only five days after the superoutburst maximum) was also observed in another star from the ER UMa subgroup - ER UMa itself (Kato et al. 2003a). It was interpreted as a sudden switch to so-called late superhumps usually occurring during late stages of superoutburst in ordinary SU UMa stars. As we will see later, the origin of this phase reversal has a completely different source.

5.3 Additional modulation as a source of phase reversal

From each light curve of IX Dra in superoutburst we removed the first or second order polynomial and analyzed them using ANOVA statistics with two harmonic Fourier series (Schwarzenberg-Czerny 1996). The resulting periodogram is shown in Fig. 8. The most prominent peak is found at a frequency of $f_1 = 14.926 \pm 0.008$ c/d, which corresponds to the period of $P_{sh} = 0.06699(4)$ days. The first harmonic of this frequency at $f_2 = 29.86 \pm 0.05$ c/d is also clearly visible.

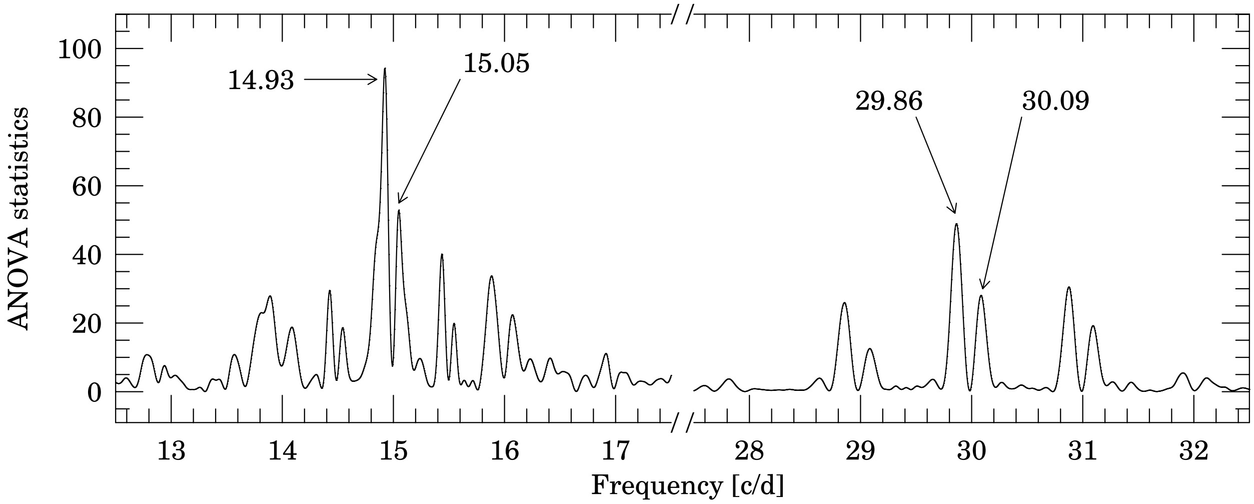

Figure 8: ANOVA power spectrum of the light curve of IX Dra during its 2003 September superoutburst.

Combining this determination with the superhump period obtained from the $O-C$ analysis, we conclude that the mean superhump period during the 2003 September superoutburst of IX Dra was $P_{sh} = 0.066968(17)$ days (96.43 ± 0.02 min).

A very interesting feature of the power spectrum shown in Fig. 8 is a double structure of the main peak, which is visible both for the main frequency and its first harmonics. The secondary peak appears at $f_3 = 15.049 \pm 0.013$ c/d, which corresponds to $P_3 = 0.06646(6)$ days, and its first harmonic at $f_4 = 30.09 \pm 0.05$ c/d.

The peak at f_3 is our *Rosetta stone* for understanding the unusual phase reversal seen in IX Dra and ER UMa. It is easy to find that the difference between the two main frequencies f_1 and f_3 is equal to the beat frequency $f_{beat} = 0.123$ c/d. This corresponds to a period of 8.1 days. This means that at the beginning of superoutbursts both waves oscillate in one phase, thus we detect clear superhumps with a large amplitude of 0.27 mag. After half of the beat cycle (~ 4 days) the waves are shifted in phase by 0.5. Thus the maximum of the modulation characterized by P_3 occurs exactly in the place of birth of the secondary humps. The amplitude of the secondary humps is then increased by the second wave and they became stronger than the main maxima.

To check if our interpretation is correct, we decided to perform prewhitening of the light curve of IX Dra from the superoutburst. The raw light curve from the period Sep 20-26, with the general decreasing trend removed, was fitted with two sine series corresponding to the two periods and their five harmonics:

$$rel.\, mag = A_0 + \sum_{j=1}^{6} A_j^1 \sin(2j\pi t/P_{sh} + \phi_j^1) + \sum_{j=1}^{6} A_j^3 \sin(2j\pi t/P_3 + \phi_j^3) \qquad (2)$$

Knowing A_j^1 and ϕ_j^1 we were able to remove the term containing P_{sh} and obtain pure modulations with P_3. The resulting light curve, folded on the period $P_3 = 0.06646$ days and averaged in 0.02 phase bins, is shown in Fig. 9.

On the other hand, knowing A_j^3, ϕ_j^3 and P_3 we can remove the variability with P_3 and investigate the pure superhump profiles. This has been done in Fig. 10, where we show individual light curves from 2003 September superoutburst prewhitened with P_3. These light curves are phased with P_{sh} and averaged in 0.05 phase bins.

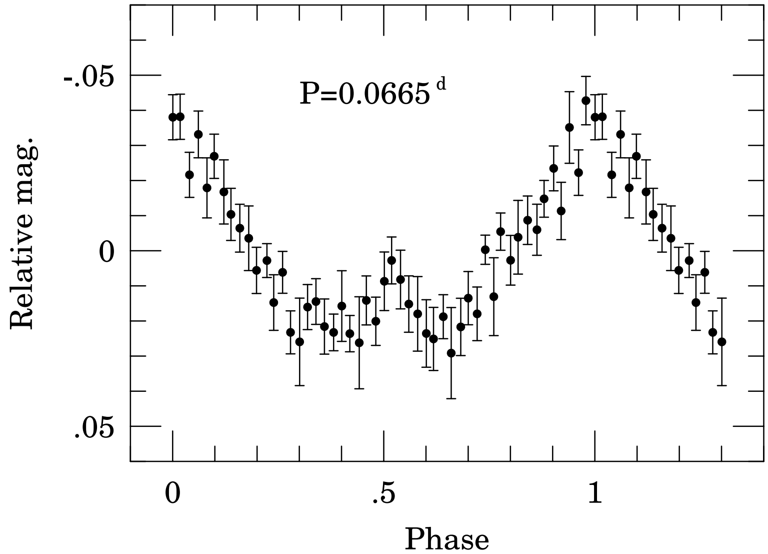

Figure 9: The light curve from 2003 September superoutburst prewhitenned with P_{sh} and folded with the period of $P_3 = 0.06646$ days.

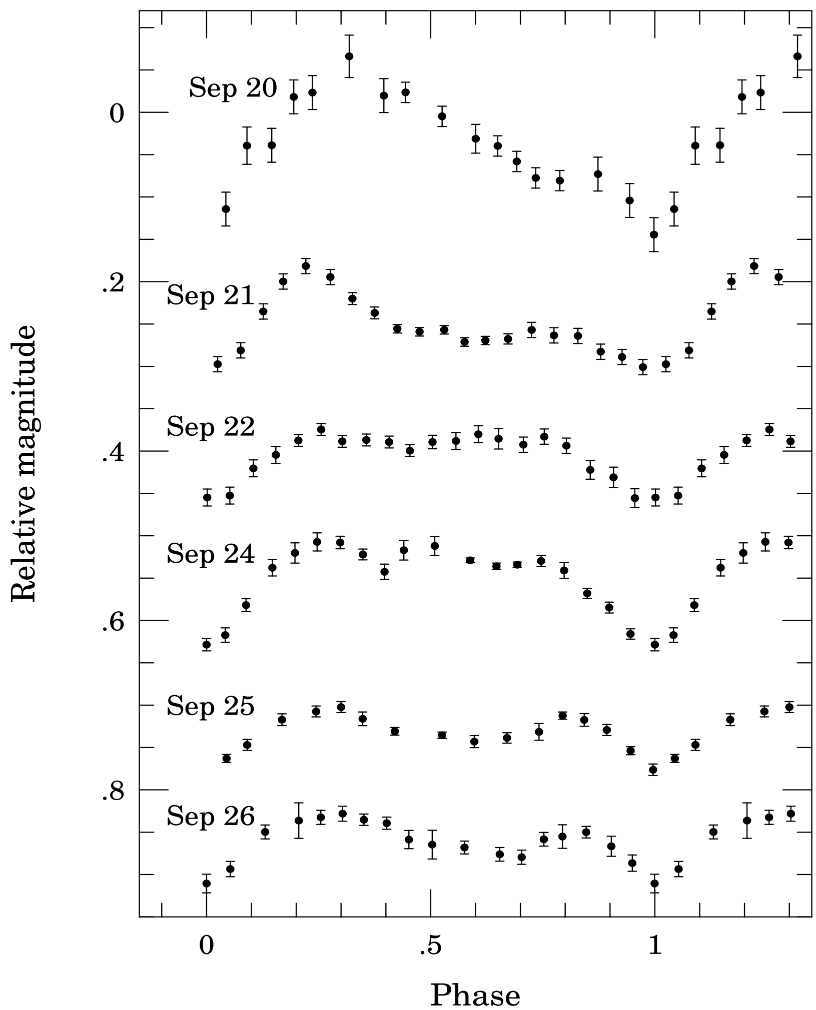

Figure 10: Amplitude and profile changes of superhumps during the 2003 September superoutburst of IX Dra after removing the variability with the second period present in the light curve (P_3).

It is now clear that there is no phase reversal, the first maximum is always the primary one, and superhumps behave as in normal SU UMa star.

The same situation is in ER UMa. Its superhump period, according to Kato et al. (2003a), is $0.06558(6)$ days ($f = 15.25$ c/d). The orbital period of the system determined from the radial velocity study of Thorstensen et al. (1997) is $0.06366(3)$ days ($f = 15.71$ c/d). Thus, the beat period between these two periods should be around 2.2 days. Looking at the THETA diagram of Kato et al. (2003a) shown in their Fig. 3, it is easy to find the peak at frequency of 15.7 c/d, which can be associated with the orbital period of the binary. The prewhitening of light curves of Kato et al. (2003a) should certainly show that the peak at frequency of 15.7 c/d is real, corresponds to the orbital period and is responsible for phase reversal.

6 The August 2003 superoutburst

Our observations from Aug 4 to Aug 8 caught the star at the end of the superoutburst. The clear superhumps are visible in each night, including the night of Aug 8 when the star faded almost to quiescence.

Fig. 11 shows the ANOVA power spectrum for the four nights of the August superoutburst, with the overall brightness decrease removed. The highest peak is found at the frequency $f = 14.98 \pm 0.04$ c/d which corresponds to the period of $P_{sh} = 0.06674(18)$ days. This value agrees well with the value of P_{sh} obtained for the September superoutburst. This is another argument for a constant superhump period during the entire superoutburst, because in September we covered the first and middle phases of the superoutburst and its late stages in August.

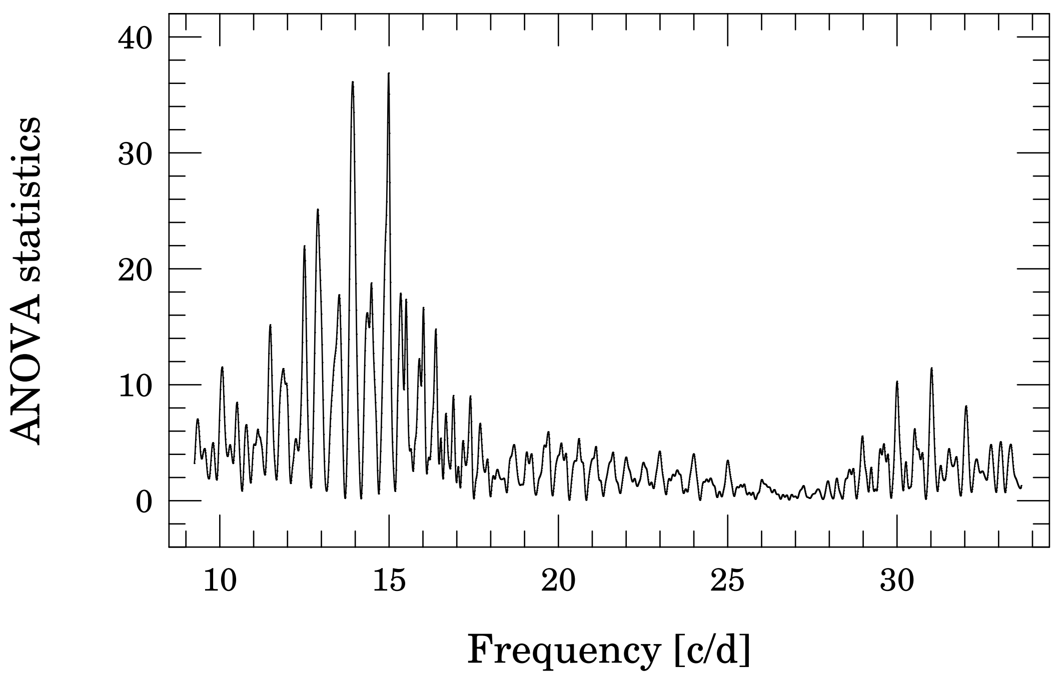

Figure 11: ANOVA power spectrum of the light curve of IX Dra during its 2003 August superoutburst.

7 Nature of the second modulation and its implications

7.1 Evolution of CVs

Typical dwarf nova starts its evolution as a binary stystem containing $\sim 0.6\mathcal{M}_\odot$ white dwarf and $0.2 \div 0.5\mathcal{M}_\odot$ main sequence secondary. At the beginning, the orbital period is of ~ 10 hours and decreases due to angular momentum loss ($\dot{J}$) through the magnetic braking via a magnetically constrained stellar wind from the donor star (Hameury et al. 1988, Howell et al. 1997, Kolb and Baraffe 1999, Barker and Kolb 2003). At this stage the mass-transfer rates are typically at the level of $10^{-10} \div 10^{-8}$ $\mathcal{M}_\odot$ yr^{-1}. The CV evolves towards shorter periods until the secondary becomes completely convective and magnetic braking greatly reduces. This happens for an orbital period of around 3 hours. The mass transfer significantly decreases and the secondary shrinks towards its equilibrium radius, below the Roche lobe. Abrupt termination of magnetic braking at $P_{\rm orb} \sim 3$ hr produces a sharp 2-3 hr period gap in dwarf novae distribution. The binary reawakens as a CV at $P_{\rm orb} \sim 2$ hr when mass transfer recommences. It is then driven mainly by angular momentum loss due to the gravitational radiation ($\dot{J}_{\rm GR}$). The orbital period still decreases while mass transfer stays at almost constant level.

Paczyński (1981) was the first to find that the minimal period for a CV containing a hydrogen rich secondary is around 80 min. Modern evolution codes locate this boundary at around 65 min. At this point, the secondary star having mass of $0.06\mathcal{M}_\odot$ becomes a degenerate brown dwarf-like object and the system starts to evolve towards longer orbital periods approaching ~ 2 hr within the Hubble time. During this period the mass transfer is reduced to $\sim 10^{-12}$ $\mathcal{M}_\odot$ yr^{-1} and CV becomes a weak ($M_V \geq +12$ mag) and inactive star.

Evolution above the period gap is very fast, implying that most CVs are presently at very short periods. Kolb (1993) predicted that 99% of CVs should be below the gap and 70% of them should have "bounced" off the minimum-period limit and now be evolving back toward longer periods.

This theoretical scenario seriously disagrees with observations, especially with respect to the minimal period. A sharp period cut-off is observed around 76 min. Currently, the three dwarf novae with shortest orbital periods are GW Lib with 76.8 min, DI UMa with 78.6 min and V844 Her with 78.7 min (Fried et al. 1999, Thorstensen et al. 2002a). Thus theoretical models, placing period "bounce" at ~ 65 min, disagree with observations at the level of $\sim 10\%$. We do not deal here with two clear outliers with extremely short periods: V485 Cen (Olech 1997) and 1RXS J232953.9+062814 (Uemura et al. 2002, Thorstensen et al. 2002b) which are most probably CVs which were formed with fairly old and massive brown dwarf donors and thus can populate the period regime shortwards of the "bounce" period (Kolb and Baraffe 1999).

There have been several hypothesis trying to explaining this discrepancy. Patterson (1998, 2001) suggested that increasing the angular momentum loss below the period gap to $\dot{J} \approx 2-3\dot{J}_{\rm GR}$ would solve the problem. King et al. (2002) showed that an intrinsic spread in minimum periods resulting from a genuine difference in some parameter controlling the evolution can solve the problem. The most probable second parameter might be different admixtures of magnetic stellar wind braking in a small part of systems. Barker and Kolb (2003) proposed that the additional source of angular momentum loss might be the mass loss from the system. However, the efficiency of this process would have to be very large to move "bounce" period from 65 to 70 min.

Barker and Kolb (2003) also suggested that tidal deformation of the secondary may have an effect on the period minimum. However, realistic deformations increase the period minimum from 65 only to around 69 min.

It has also been suggested that the currently observed period minimum is not a true minimum due to an age effect (King and Chenker 2002, Barker and Kolb 2003). Simply, the systems which are currently at 75-77 min have not had sufficient time to evolve to the true period "bounce".

The latest results of Andronov et al. (2003), based on data from open clusters, show that empirical angular momentum loss from the secondary is much longer than predicted by earlier models, and that the secondary star is in thermal equilibrium above and in the period gap. Including angular momentum loss from the secondary in the form suggested by Andronov et al. (2003) improves the agreement between theory and observations in determining the period minimum. Their data show that angular momentum loss for systems below period gap is at the level of 1.5 larger than resulting from gravitational radiation alone. This is still smaller that the value of 2-3 times suggested by Patterson (1998, 2001).

Another serious discrepancy between theory and observations lies in the orbital period distribution. According to the theoretical models (Kolb 1993, Howell et al. 1997, Barker and Kolb 2003), the Galaxy is old enough to have 99% of its CVs below the period gap. As many as 70% of them should have reached their period minimum and to be currently evolving towards longer periods. These CVs are predicted to have very low mass transfer rates ($\dot{M} \leq 10^{-11}\ \mathcal{M}_{\odot}\ \mathrm{yr}^{-1}$) and low time averaged absolute brightness ($M_V \geq +10$ mag). This should create a clear period spike close to the minimum period, but observations show that the period distribution below period gap is flat (Patterson 1998).

In fact, we currently know only four CVs which can be assumed to be potential period bouncers. They are WZ Sge, AL Com, EG Cnc and DI UMa. The three former objects form a quite homogeneous group showing large eruptions typically once per decade and no ordinary outbursts. Their mass transfer rates are low and they are very faint objects with $M_V \sim +12$ mag. On the other hand, DI UMa belongs to the very active group of ER UMa stars. It goes into superoutburst every 30-45 days and into ordinary outburst every 8 days (Kato et al. 1996, Fried et al. 1999) indicating very high mass transfer rate.

All these four objects have orbital periods very close to the period cut-off. Thus, from the observational point of view there is no clear evidence for the period "bounce". One can simply assume that there is a larger dispersion in period excess for stars having short orbital periods. A discovery of a star with the period excess below 1% and an orbital period significantly longer than 80 min would be strong evidence for period "bounce".

7.2 The period excess versus the orbital period

The superhump period is simply the beat period between the orbital and precession rate periods:

$$\frac{1}{P_{sh}} = \frac{1}{P_{orb}} - \frac{1}{P_{prec}} \tag{3}$$

The precession rate of the eccentric disc was first discussed by Osaki (1985). Based on a non-resonant free-particle orbit at the disk edge he derived the following expression for the precession rate:

$$\frac{P_{orb}}{P_{prec}} = \frac{3}{4}\frac{q}{\sqrt{1+q}}\left(\frac{R}{a}\right)^{3/2} \tag{4}$$

where a is the binary separation, R is the disc radius and q is the mass ratio M_2/M_1. At the 3:1 resonance we can assume that $R \approx 0.46a$ and hence:

$$\frac{P_{orb}}{P_{prec}} \approx \frac{0.233q}{\sqrt{1+q}} \tag{5}$$

Defining the period excess ε as:

$$\varepsilon = \frac{\Delta P}{P_{orb}} = \frac{P_{sh} - P_{orb}}{P_{orb}} \tag{6}$$

and using equation (5) we can simply derive the relation between the period excess and the mass ratio:

$$\varepsilon \approx \frac{0.23q}{1+0.27q} \tag{7}$$

From the observational point of view it was first noticed by Stolz & Schoembs (1984) that ε grows with P_{orb}. This relation is obeyed not only by the ordinary SU UMa stars but also by the permanent superhumpers (Skillman & Patterson 1993).

Direct measurements of mass ratio q in CVs yields the following relation:

$$\varepsilon = 0.216(\pm 0.018)q \tag{8}$$

which roughly agrees with the theory (Patterson 2001).

Due to the mass loss from the secondary, the mass ratio q decreases with time. Thus it is very useful to trace the evolution of cataclysmic variable stars in the $\varepsilon - \log P_{orb}$ plane.

7.3 IX Dra and its place in the family

The longer period detected during the September superoutburst of IX Dra is easily interpreted as the period of the superhumps. The most reasonable explanation for the shorter period is that it is the orbital period of the system. This then makes IX Dra a unique object for two reasons:

1. it is the first star, whose orbital period is visible throughout the superoutburst,
2. it has an unusually small period excess of $0.76\% \pm 0.03\%$ (a lower value has been observed only in EG Cnc - Patterson et al. 1998).

Since the period excess is known to scale with mass ratio (see equations 7 and 8) the period difference observed in IX Dra corresponds to a mass ratio of $q = 0.035 \pm 0.003$. Assuming a typical white dwarf mass of between $0.6 - 0.8\mathcal{M}_\odot$, the secondary component must have a mass lower than $0.03\mathcal{M}_\odot$. Even in the case of an extremely massive white dwarf close to the Chandrasekhar limit, the secondary component of IX Dra could not have a mass greater than 0.045 solar masses, which makes it the best candidate among dwarf novae (alongside EG Cnc) for a brown dwarf.

The only class of stars in which one observes changes with a period equal to the orbital period during a superoutburst are WZ Sge stars, a subgroup of SU UMa stars which have very rare outbursts and very low mass transfer rates. In these stars, one does not observe superhumps during the first ~ 10 days of a superoutburst, only changes with orbital periodicity. Afterwards, the orbital humps are replaced by the usual superhumps. It has recently been suggested that this is caused by the low mass ratio in WZ Sge stars, which results in a very large disc extending to the region where its particles can enter into a 2:1 orbital resonance. This generates a two-armed spiral pattern of tidal dissipation

and is responsible for the light modulations with orbital period. Superhumps are not seen from the beginning of the superoutburst as the disc is not yet sufficiently elliptical because of the low rate of mass transfer at this time (Osaki and Meyer 2002).

The unusually low mass ratio of IX Dra suggests that, during a superoutburst, the accretion disc extends to 80% of the distance between the components of the system (see Figs. 1 and 2 in Osaki and Meyer). This is analogous to the behavior of WZ Sge stars. However, unlike in their case, IX Dra is characterized by a mass transfer rate at least an order of magnitude higher. Thus, even at the start of the superoutburst the disc is large, massive and eccentric, allowing both the 2:1 and 3:1 resonances to occur. The disc precesses, and therefore both orbital humps and superhumps can be observed throughout the entire superoutburst.

Fig. 12 shows the position of IX Dra in the period excess vs. orbital period diagram. Points mark normal SU UMa stars, squares correspond to the permanent superhumpers while open circles indicate the WZ Sge dwarf novae with recurrence times of 10 – 30 years (WZ Sge, AL Com, EG Cnc) and the star DI UMa, which has frequent outbursts like IX Dra. Two other frequently outbursting dwarf novae: ER UMa and V1159 Ori are shown with triangles. This figure is shown after Patterson (1998, 2001) with over 20 new objects being added from Patterson et al. (2003) and Olech et al. (2003b). The solid line shows the evolutionary path of a dwarf nova with a white dwarf of mass $0.75\mathcal{M}_{\odot}$ and a secondary component with effective radius 6% larger than that of a single main sequence star (due to the distortion of the star filling its Roche lobe - Renvoizé et al. 2002).

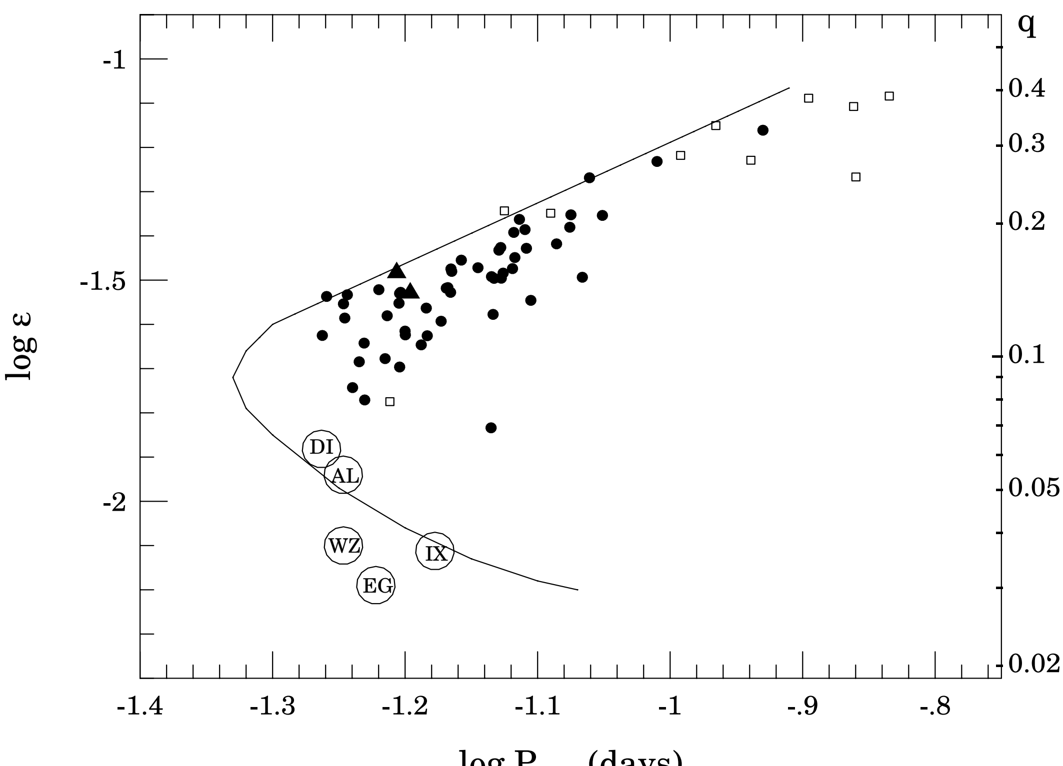

Figure 12: The relation between the period excess and orbital period of the system. The solid line corresponds to the evolutionary track of a binary with a white dwarf of $0.75\mathcal{M}_{\odot}$ and a secondary with effective radius 6% larger than in the case of an ordinary main sequence star. Calculations are made under the assumption that below the orbital period of two hours the angular momentum loss in only due to gravitational radiation.

Looking at this picture we can see that the theoretical models do not agree too well with observations. There are three ways of lowering the theoretical line to better fit the observational data:

1. increasing the white dwarf mass up to $1.1-1.2$ solar masses,
2. increasing the effective radius of the distorted secondary by an unrealistic value of 20% (Renvoizé et al. 2002),
3. assuming that stars with periods below 2 hours lose angular momentum about $2-3$ times more effectively than in the case of gravitational waves alone (Patterson 1998, 2001).

Hypothesis (3) is the most tempting, since it accelerates the evolution of the system, moving the line down and increasing the minimum period from 65-70 minutes up to 75 minutes, which agrees very well with observations (the ordinary dwarf nova with the shortest known orbital period is GW Lib with $P_{orb} = 76.78$ minutes - Thorstensen et al. 2002a).

Our discovery places IX Dra among the most evolved objects. According to the theory they should have very low absolute brightness (+12 mag) and very low accretion rates. However, both IX Dra and another atypical star, DI UMa, have the highest accretion rates observed in SU UMa stars, resulting in their high level of activity in the form of frequent outbursts and superoutbursts (Osaki 1995, Hellier 2001, Buat-Ménard and Hameury 2002). Therefore, we conclude that very old dwarf novae, which most of the time are quiescent and behave like WZ Sge stars (with outbursts every 20 years or more) occasionally show greatly increased activity with a high accretion rate. DI UMa and IX Dra are currently in this state. This high accretion rate may cause the mass loss from the system, supplementing the emission of gravitational waves as the cause of angular momentum loss.

8 Normal outbursts

In total, we detected seven ordinary outbursts of IX Dra. Three of them with the best coverage are shown in Fig. 13. As in other SU UMa stars, near the maximum of normal outburst IX Dra shows no other large amplitude oscillations except small flickering. However at around 0.5 mag below the maximum the star often starts to show clear modulations.

The periodogram for nights from Aug 22 to Aug 25 is inconclusive, showing many peaks of similar power in the frequency range 12 – 16 c/d.

During the next outburst, which occurred on Aug 30, IX Dra was caught at maximum light and during this night we did not detect any periodic modulations. Our 3.9-h run on Aug 31 found the star at magnitude 0.8 mag fainter, showing clear modulations with amplitude of around 0.25 mag. The power spectrum for this run shows a broad peak at frequency of 15 c/d. The distance between two most prominent maxima is 0.132 d, indicating a period of about 0.066 days.

The most conclusive results were obtained for the outburst lasting from Sep 13 to Sep 16. The ANOVA power spectrum for these nights shows a clear peak at frequency of 15.06 ± 0.07 c/d, corresponding to the period of $0.0664(3)$ days. This value is in very good agreement with the value of the orbital period derived from the September superoutburst. On the other hand, it is only 2σ from the value of superhump period.

An interesting feature visible in Fig. 13 are the clear dips in the light curve of IX Dra observed at HJD of 874.44, 877.5 and 896.53. They appear aperiodically and their nature is unknown.

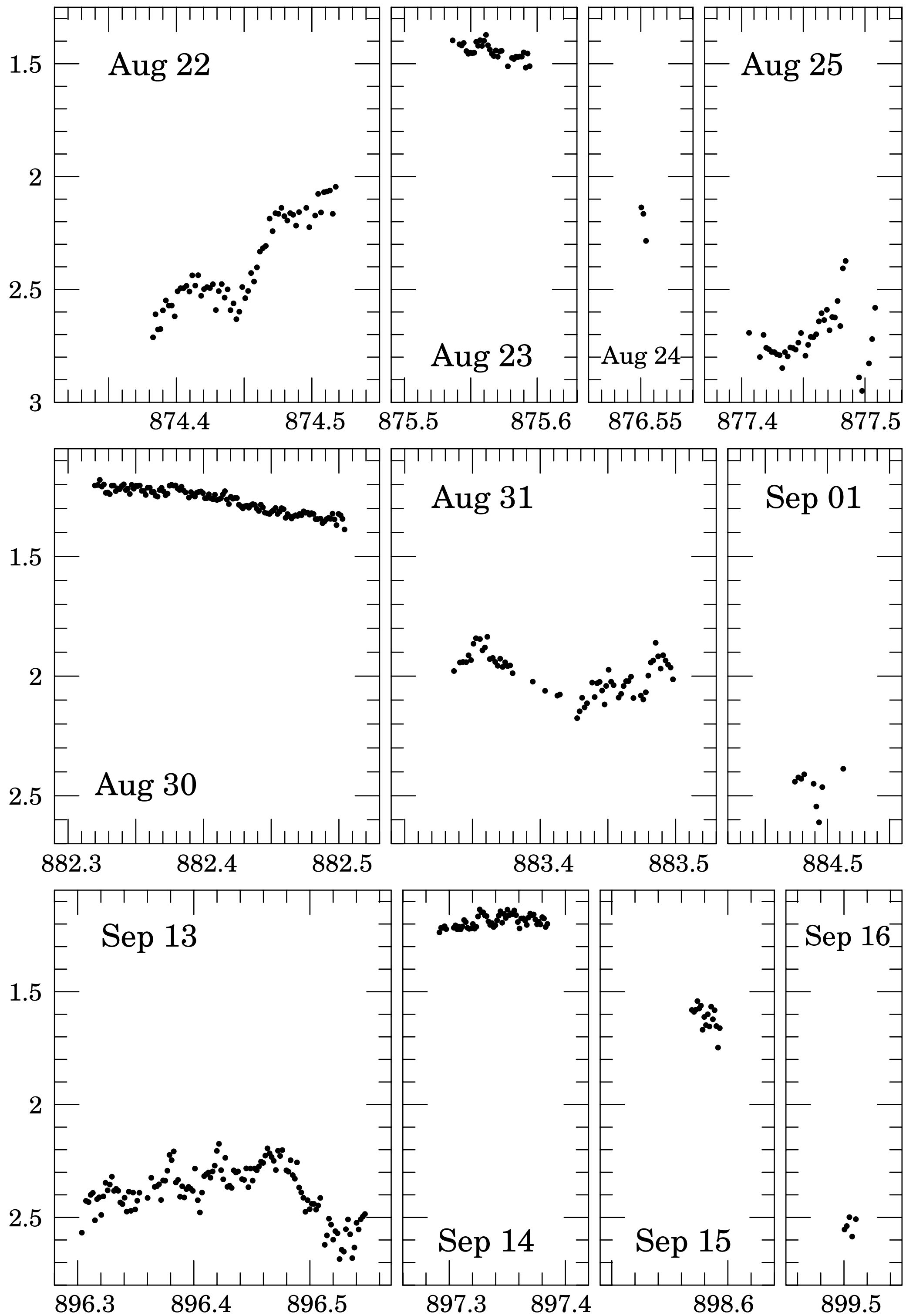

Figure 13: The light curves of IX Dra during three normal outbursts, whit the best observational coverage.

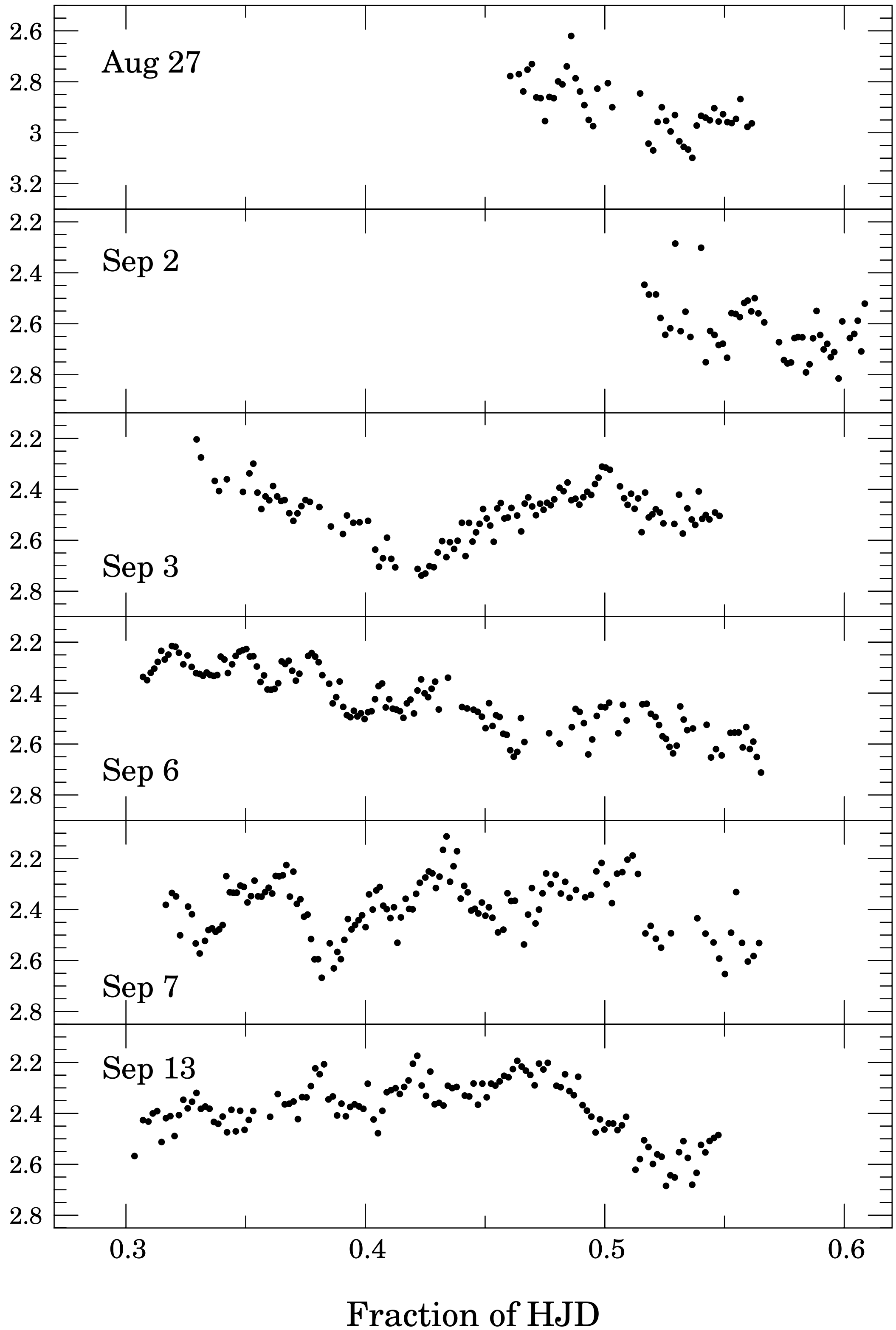

Figure 14: The light curves of IX Dra from six longest runs during quiescence.

Finally, we conclude that during ordinary outbursts IX Dra occasionally shows orbital humps. However, we can not exclude that, within errors, they are in fact superhumps or negative superhumps, such as were detected in V1159 Ori during its outbursts (Patterson et al. 1995).

9 Quiescence

Fig. 14 shows the light curves of IX Dra in quiescence obtained during the six longest runs. The ANOVA power spectrum for interval Sep 6–13 is shown in the upper panel of Fig. 15. Before calculation, the light curves were prewhitened using a first order polynomial. It is clear that the highest peak corresponds to a frequency of 13.05 c/d. However, we do not assume that this is the true period, but rather a 2-day alias of the peak found at $f = 15.03 \pm 0.03$. The latter frequency corresponds to a period of $P_{orb} = 0.0665(1)$. This value agrees very well with our determination made for the September superoutburst and in normal outbursts.

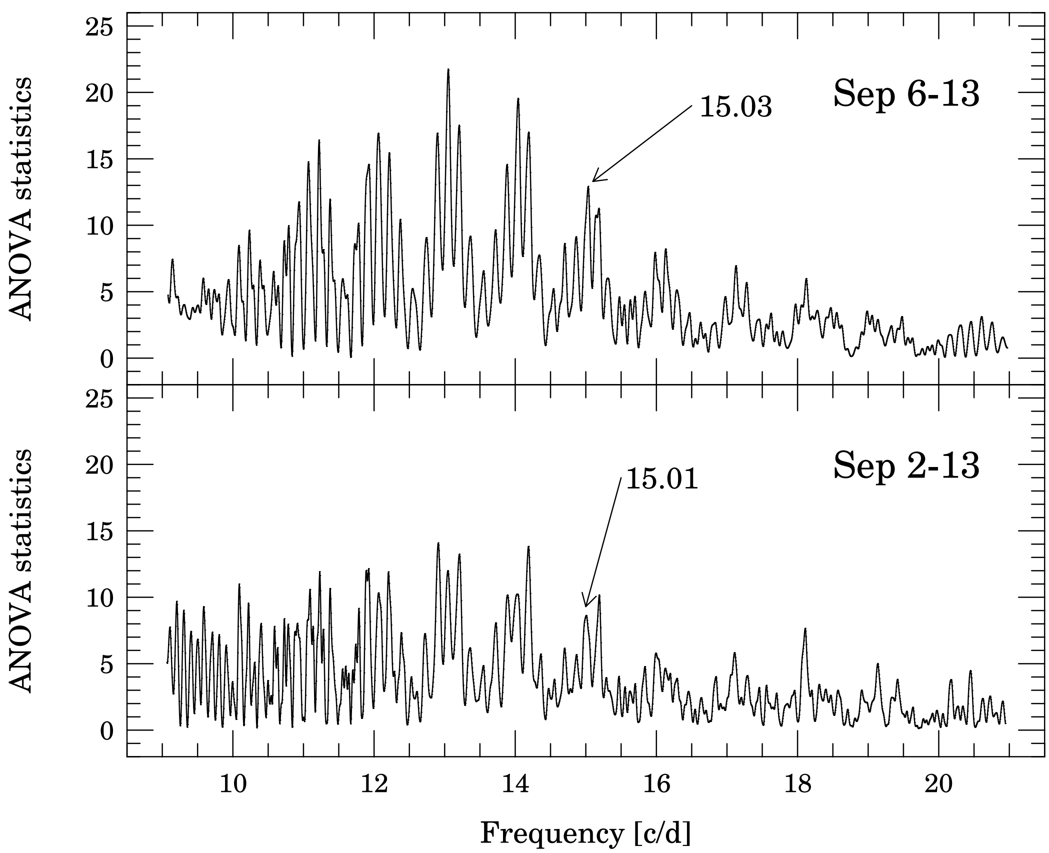

Figure 15: The ANOVA power spectrum for Sep 6–13 (upper panel) and Sep 2–13 (lower panel).

The question is why are the 1-day and 2-day aliases from Fig. 15 higher than the true peak for both intervals Sep 6–13 and Sep 2–13. The explanation might lie in high amplitude flickering, which masks the weak orbital signal, and in mysterious wide dips which are clearly visible during nights of Sep 3 and Sep 13. They add signal to the lower frequencies, increasing low frequency aliases to a level higher than the main peak.

The main conclusion of this section is that, in quiescence, IX Dra shows a weak signal with a period of $0.0665(1)$ days, i.e. with the same value as was observed in the September 2003 superoutburst, supporting the hypothesis that it is the orbital period of the binary system.

10 IX Dra as a member of the ER UMa-type dwarf novae

In the mid 1990s, when the first three members of the ER UMa group were discovered, they seemed to be very unusual compared to normal SU UMa stars. The ordinary SU UMa star with the shortest supercycle of 134 days was YZ Cnc (Patterson 1979, Shafter and Hessman 1988). Thus supercycles of ER UMa stars were about 3-4 times shorter. However, Patterson et al. (1995) describing the results of the CBA observational campaign for V1159 Ori, claimed that there is no reason for introducing a new class of variable stars. Simply, the observable traits of ER UMa-type stars seem to be consistent with garden-variety SU UMa stars. They follow the Kukarkin-Parengo relation connecting the amplitude of the outburst with recurrence time between normal outbursts (Kukarkin and Parenago 1934) and the Bailey relation connecting decay times from normal eruptions and orbital period of the binary (Bailey 1975). They simply appear to be normal SU UMa stars with greater activity and greater luminosity due to their higher mass transfer rates (Osaki 1995).

However, careful inspection of the diagram with recurrence intervals for supermaxima vs. normal maxima showed a significant gap between normal SU UMa stars and ER UMa-type variables (see Fig. 18 of Paterson et al. 1995).

Since then, we have come to better understanding of the ER UMa stars. In particular, for four of them we know the orbital periods and we can put them into the $\varepsilon - P_{orb}$ plane. This is shown in Fig. 12, where DI UMa and IX Dra are plotted with open circles and ER UMa and V1159 Ori with triangles. It is clear that ER UMa stars occupy completely different locations on this plane, having different mass ratios and different evolutionary status.

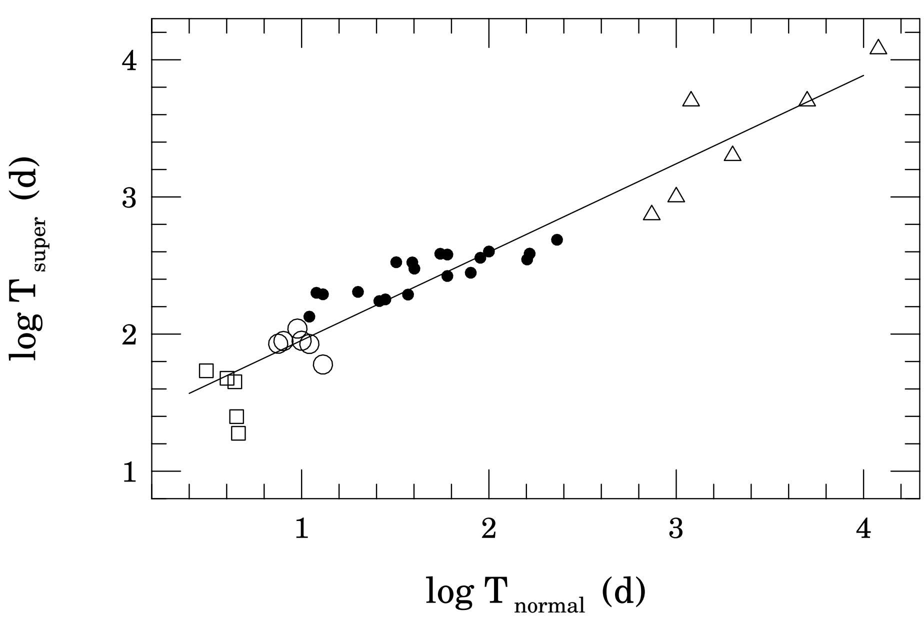

Figure 16: The relation between recurrence interval between superoutbursts and interval between normal outbursts. See text for explanation of the symbols.

The discovery of new variables of the SU UMa-type fills the above-mentioned gap in the diagram showing recurrence intervals for supermaxima vs. normal maxima. Recent discoveries of MN Dra with a supercycle of 60 days (Nogami et al. 2003), SS UMi and NY Ser with supercycles of 85 days (Kato et al. 2000, Nogami et al. 1998), V503 Cyg and BF Ara with supercycles of 89 days (Harvey et al. 1995, Kato et al. 2002a, 2003b) and V344 Lyr with supercycle of 109.6 days (Kato et al. 2002b) results in a smooth transition from the normal SU UMa stars to ER UMa-type variables. This is shown in Fig. 16, where normal stars are plotted with dots, WZ Sge variables with triangles, ER UMa stars with squares and newly discovered normal SU UMa stars with circles. A simple linear fit to the data gives the following relation:

$$\log T_s = 1.31 + 0.644 \log T_n \tag{9}$$

which is shown as solid line. It is clear that this relation describes very well both ER UMa and normal SU UMa stars.

Finally, the gap between normal SU UMa stars and ER UMa-type variables has disappeared and, in the light of new discoveries, we can see a smooth transition from one group to another. Our conclusion is similar to the statement of Patterson et al (1995) that there is no need to artificially distinguish ER UMa stars from other SU UMa variables.

11 Summary

We presented the results of the 2003 observational campaign of frequently outbursting dwarf nova IX Draconis. The main conclusions of our work are:

1. Analysis of the global light curve spanning five months of observations shows that IX Dra is a very active object and goes into superoutburst every 54 days and into a normal outburst every 3.1 days. According to the model by Osaki (1995), this is due to a very high mass rate of mass transfer from the secondary.

2. During two best observed superoutburts, we detected the clear superhumps with a period of 0.066968(17) days (96.43 ± 0.02 min). The superhump period seems to be constant during entire superoutburst.

3. During September 2003 superoutburst, a second periodicity was clearly visible in the light curve of the star. Its value was 0.06646(6) days (95.70 ± 0.09 min). A wave with the same period was detected during normal outbursts and in quiescence. We suggest that this is the orbital period of the binary system.

4. The beat between superhump and orbital period is the main cause of an unusual phase reversal of maxima of superhumps - a phenomenon which was previously observed also in ER UMa itself (Kato et al. 2003a). We suggest that careful reanalysis of observations of ER UMa from superoutburst obtained by Kato et al. (2003a) should result in discovery of the orbital period.

5. The period difference observed in IX Dra corresponds to a mass ratio $q = 0.035 \pm 0.003$. Assuming a typical white dwarf mass of $0.6 - 0.8\mathcal{M}_\odot$, the secondary component must have a mass lower than $0.03\mathcal{M}_\odot$, which makes it the best candidate among dwarf novae (alongside EG Cnc) for a brown dwarf.

6. IX Draconis is the first SU UMa star showing orbital modulations during the entire superoutburst. This is possibly due to the extremely low mass ratio which allows the edge of the disc to reach 80% of the separation of the binary. In the outer region of the disc, its particles can enter into a 2:1 orbital resonance. This generates a two-armed spiral pattern of tidal dissipation and is responsible for the appearance of the light modulations with orbital period (Osaki and Meyer 2002).

7. The position of IX Dra in the period excess vs. orbital period plane suggests that the star is the most evolved cataclysmic variable star in the Galaxy, which reached its period minimum long time ago and now evolves towards longer periods.

8. High activity of IX Dra is in clear contrast with the behavior of its neighbours in the $\varepsilon - \log P_{orb}$ plane which are mostly faint and inactive objects. Thus we suggest that very old dwarf novae, which most of the time are quiescent and behave like WZ Sge stars, show occasionally greatly increased activity with a high rate of accretion. DI UMa and IX Dra are currently in this state. This high rate of accretion may cause mass loss from the system, supplementing the emission of gravitational waves as the cause of angular momentum loss.

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